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EXPLOSIVE-DRIVEN EMP GENERATOR

Keith M. Soo Hoo

Aerospace Corporation

Prepared for:

Space and Missile Systems Organization

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Explosive-Driven EMP Generator

Prepared by K. M. SOO HOO
Plasma Research Laboratory

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Laboratory Operations
THE AEROSPACE CORPORATION

Prepared for SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
Los Angeles, California

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FOREWORD

This report is published by The Aerospace Corporation, El Segundo, California, under Air Force Contract No. F04701-72-C-0073.

A more complete account is given in a classified report ["(U) Explosively Driven Electromagnetic Pulse Generators," ATM-73(3220-70)-1 dated 12 July 1972] issued separately.

This report, which documents research carried out from July 1971 through June 1972, was submitted to Lt Col Elliott W. Porter, DYA, on 14 August 1972 for review and approval.

Approved

R. X. Meyer

R. X. Meyer, Director
Plasma Research Laboratory

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Elliott W. Porter

ELLIOTT W. PORTER, Lt Col, USAF
Asst Dir, Development Directorate
Deputy for Technology

ABSTRACT

The feasibility of radiating large quantities of energy from a satellite is discussed. A system comprised of an explosive generator source, switching and matching networks, and a bent-dipole antenna is theoretically analyzed. The calculations indicate that an electric field of 4000 V/m can be produced at a distance of 1 mile from the source.

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FIGURES (Continued)

TECHNICAL DESCRIPTION

A. INTRODUCTION

This study is concerned primarily with the feasibility of radiating large quantities of electromagnetic energy from an orbiting satellite. It is also concerned with the energy source, the radiator (antenna), and the mechanism for coupling one to the other.

In the beginning it was necessary to bound the problem by the establishment of a set of requirements. It was assumed that the complete system may not weigh more than 500 lb, that it should produce electric fields of at least a few thousand volts per meter at a distance of one mile from the source, and that the radiated signal should contain frequency components primarily in the 20 to 50 MHz range. Additional assumptions will be made when warranted.

First, the problem of selecting a power supply must be considered. If it is assumed that the antenna has unity gain, the antenna range equation can be used to find that approximately 10^{12} W of radiated power are required to produce an electric field of 3000 V/m at a distance of one mile. If a time duration of 0.1 μsec is also assumed, which corresponds to an operating time of 2 to 5 cycles, then the required radiated energy is approximately 100 kJ.

From weight considerations alone, it is apparent that the energy source cannot be simply a capacitor bank. For example, it is reasonable to assume that capacitive energy can be supplied at approximately 70 J/lb. At this rate, a realistic system, which must overcome energy lost in the conversion from capacitive to electromagnetic energy, may easily exceed the 500-lb weight limit many times over.

In contrast to this, about ten times the required energy is available in just 1 lb of explosive. Of course, to suggest the use of explosives is tantamount to assuming that destruction of the satellite would be permissible after the required electromagnetic energy has been released. Methods for converting

explosive to electromagnetic energy have been in existence for several years.[1-3] These devices have been referred to as "explosive-driven flux compression devices," or simply as "explosive generators." In all of these devices, a capacitor initially supplies a small amount of energy, which is then amplified by the explosive generator. Conversion to electromagnetic energy is obtained by the compression of magnetic flux as the explosive forcibly reduces the inductance of enclosing circuits.

Recently an explosive generator system was designed for an upper atmospheric physics program.[4] The power supply consisted of an 18 kJ capacitor bank that supplied the initial energy to a LASL Mark V explosive generator, which in turn drove a second-stage Sandia 169 explosive generator. This two-stage system weighed less than 500 lb and delivered approximately 350 kJ to a plasma gun.

The purpose of the foregoing discussion is to suggest that the technology may already exist with which the required system can be designed. An analysis of such a system is presented in the paragraphs that follow.

B. EXPLOSIVE GENERATOR

Detailed descriptions of the explosive generator are contained in the references given previously. The discussion here will involve primarily those details that will be used in later calculations. Also, this discussion will be confined to the Sandia Models 106 and 169, for which considerable information exists.

The operating principle of either generator is shown in Fig. 1. As shown, the generator consists of a cylindrically wound spiral concentric with an explosively loaded metal armature. An external capacitor bank establishes initial current in the winding and armature. Following this, the inductance of the generator is forcibly reduced by explosively expanding the armature, with a consequent increase in current. As shown in Fig. 1, the explosive is detonated simultaneously at both ends, and the output terminals are located at the center of the helix. In this manner, over 6 MA of current has been delivered into load inductances up to 70 nH (Model 169).

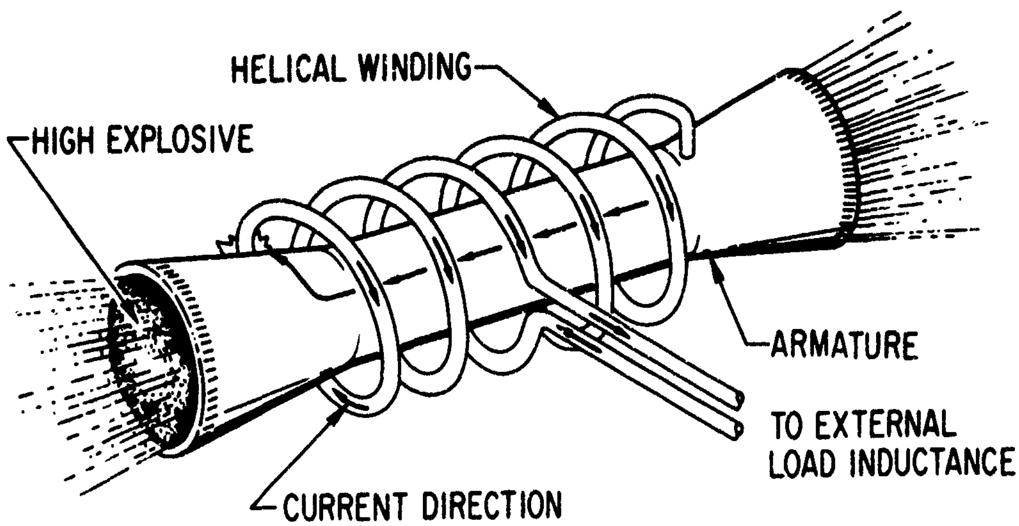


Figure 1. Operating principle of the Sandia generator.

Some of the data on the Sandia Model 106 taken from Ref. 1 are presented in Figs. 2 and 3. Figure 2 shows the generator inductance and resistance as measured from crowbar time ($t = 0$) to when the armature strikes the output terminals. Figure 5 shows the output current as it grows from a starting current of 0.118 MA at crowbar time (17.5 μsec after detonation) to a peak value of 2.6 MA. The calculated current was based on a numerical integration of the circuit equation derived from the equivalent circuit shown in Fig. 4 (L_g and R_g are the generator inductance and resistance of Fig. 2 and L_ℓ is the load inductance). It can be seen that this simple equivalent circuit provides good agreement between theory and measurement.

Finally, it should be noted that the initial current shown in Fig. 3 was supplied by a 140 kJ capacitor bank charged to 16 kV. In the two-stage device mentioned previously, the initial current, which was supplied by the first stage explosive generator, had a slightly lower value of 75,000 A.

C. DIRECT COUPLING TO A DIPOLE

Because a high-gain antenna would not be practical at the frequencies of interest, it is not necessary to become involved with the standard tradeoff between a high-gain antenna system that requires a pointing mechanism and an omnidirectional antenna system that requires more power. Instead, a linear dipole will be considered as the basic antenna structure, as it is both simple in design and simple to analyze. The dipole does have two null directions in its radiation pattern, but these nulls can be filled by bending both antenna arms forward.

A logical starting point is to investigate what happens when the antenna is directly coupled to the generator output terminals. This problem can be analyzed by the use of equivalent circuits. The antenna is represented by an equivalent circuit of passive, lumped elements that approximate the antenna input impedance over a specified range of frequencies. Solution of the equivalent circuit representing both generator and antenna then gives the time-dependent current at the antenna terminals. The radiation field is taken as the

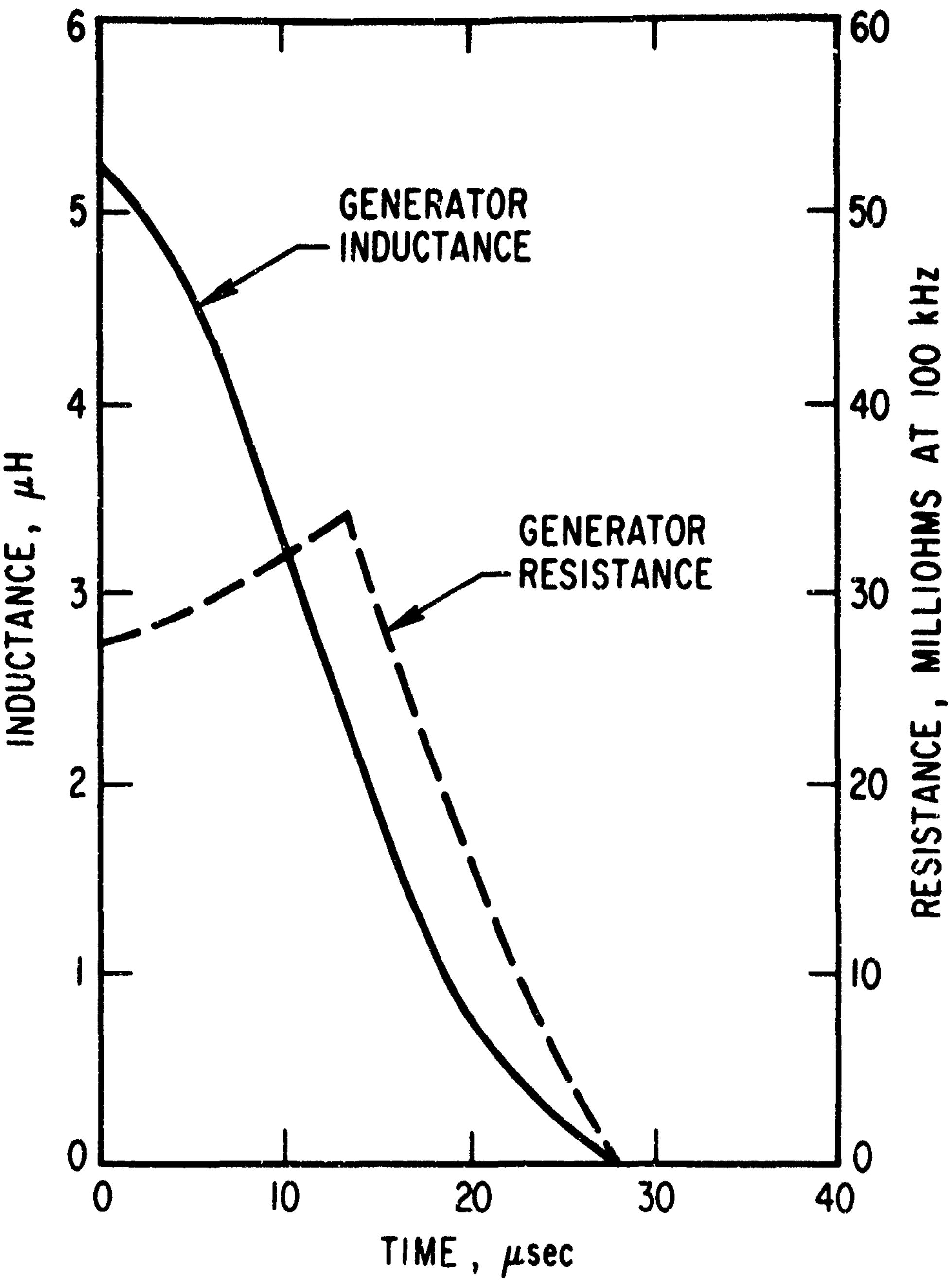


Figure 2. Sandia Model 106 generator.

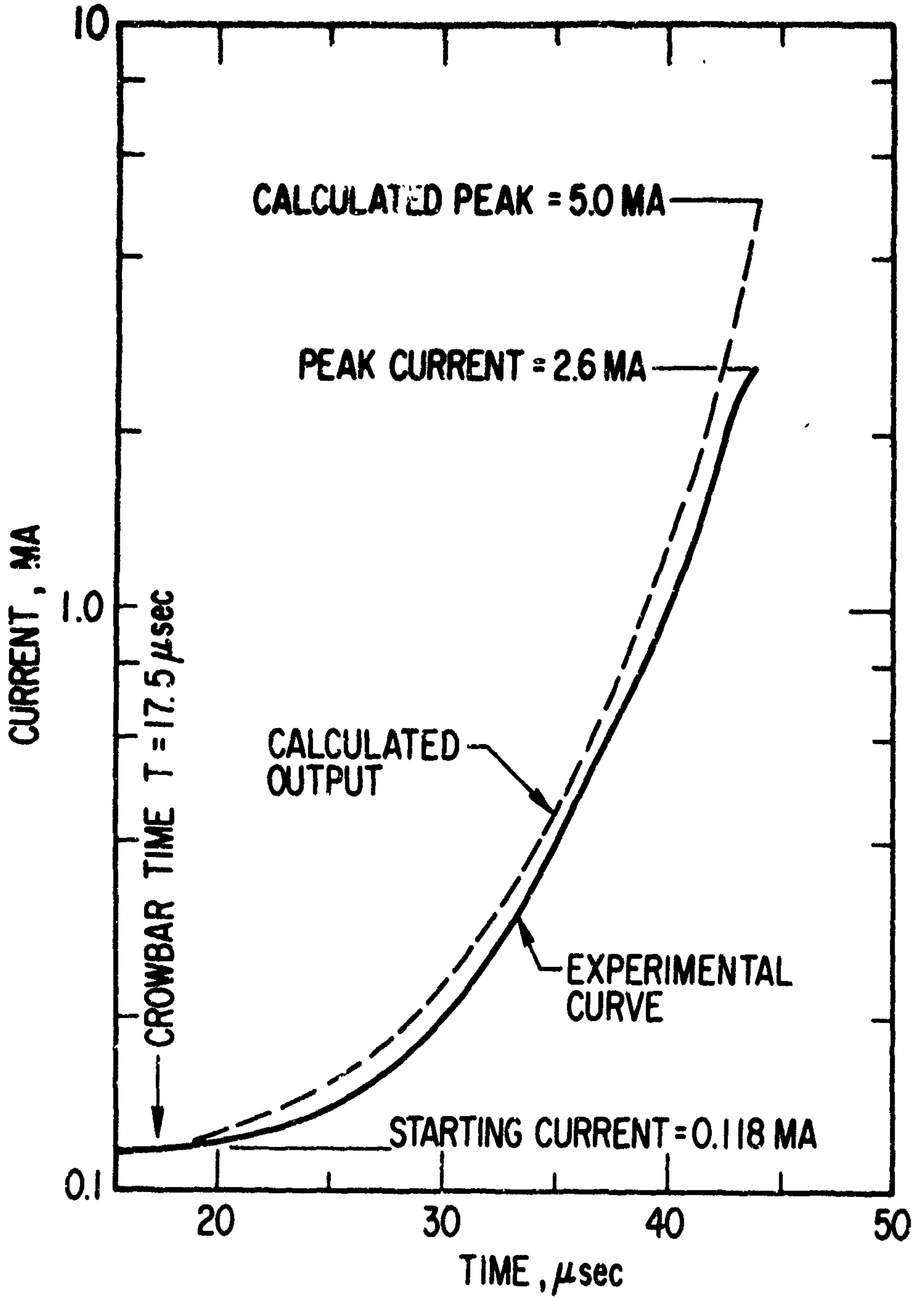


Figure 3. Comparison of the output current of Sandia Model 106 generator with that calculated by the computer code.

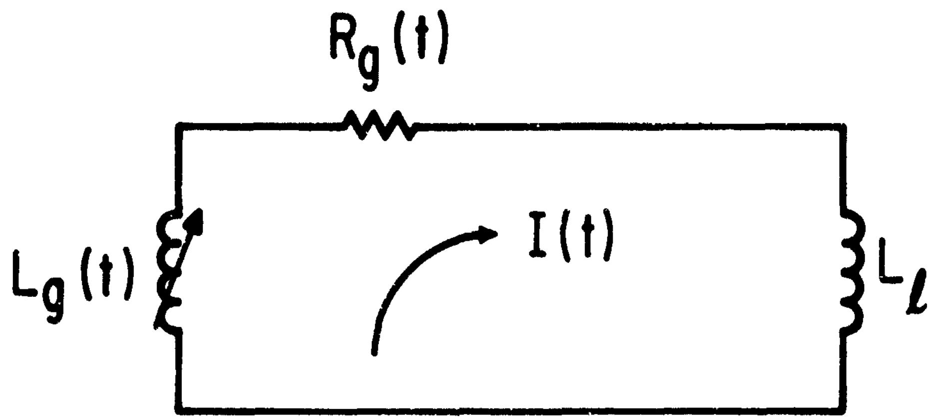


Figure 4. Basic explosive generator and its load inductance.

field from an infinitesimal dipole carrying the computed input current. The maximum electric field at a distance r from the source is therefore

$$E_{max} = \frac{\mu_o h}{4\pi r} \frac{di}{dt} \tag{1}$$

where μ_o is the magnetic permeability, h is the antenna total length, and i is the input current. Retardation effects are not of interest in the present problem and are therefore excluded from Eq. (1).

The method just described can be improved upon by a more rigorous solution of the antenna problem. In particular, an integro-differential equation can be derived for the unknown, time-dependent current distribution on the antenna, which satisfies the boundary conditions on the antenna and accounts for the presence of a driving function (the generator equivalent circuit). Numerical techniques have been developed for solving such equations.[5,6] Both the near and far fields are then easily found by integrating over the current distribution.

An equivalent circuit with a series RLC representing the antenna is shown in Fig. 5. The series RLC circuit is a reasonable approximation in the vicinity of the antenna resonant frequency. The unknown current satisfies the following differential equation

$$\frac{d^2}{dt^2}(L_g i) + L\frac{d^2 i}{dt^2} + \frac{d}{dt}(R_g i) + R\frac{di}{dt} + \frac{1}{c}i = 0 \tag{2}$$

Equation (2) does not have a closed form solution. Suppose, however, that an interval of time is considered in which the generator parameters are slowly varying. The following assumptions can be made:

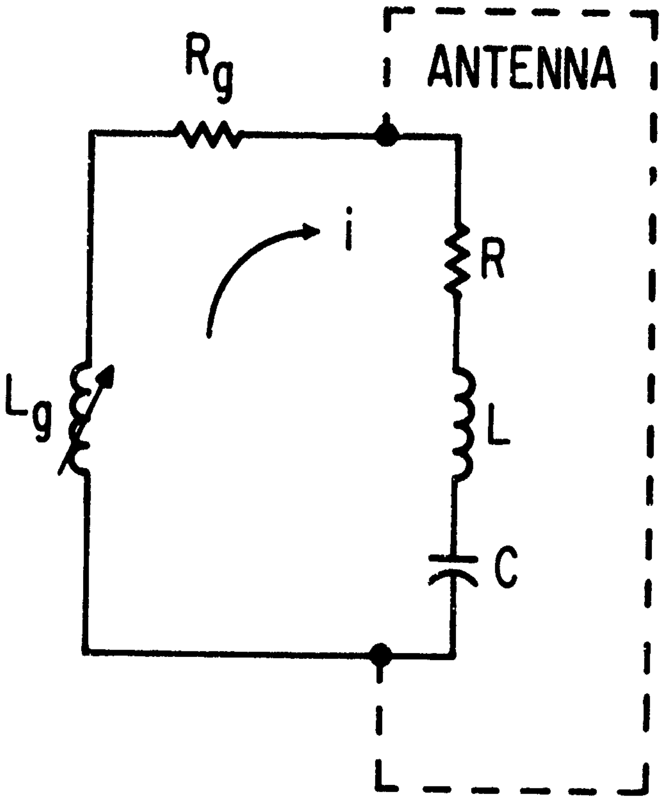


Figure 5. Explosive generator and directly coupled antenna.

$$L_g(t) \cong \overline{L_g}$$

$$L_g'(t) \cong \dot{L}_g$$

$$L_g''(t) \cong 0$$

$$R_g(t) \cong \overline{R_g} \tag{3}$$

where $\overline{L_g}$, $\dot{L}_g$, and $\overline{R_g}$ are constants. The solution to Eq. (2) will then be of the form

$$i(t) \sim e^{-\alpha t} \cos(\beta t + \phi) \tag{4}$$

where

$$\alpha = \frac{2\dot{L}_g + \overline{R_g} + R}{2(\overline{L_g} + L)} \tag{5}$$

and

$$\beta \cong \frac{1}{[C(L_g + L)]^{1/2}} \tag{6}$$

and ϕ is the phase factor. For $\alpha > 0$, Eq. (4) exemplifies an oscillating current that decays with time. For this case, the generator fails to provide any amplification, and there is no improvement over simply discharging the capacitor bank directly into the antenna.

Thus α must be negative. It can be seen from Eq. (5) that this is possible, as $\dot{L}_g$, the time rate of change of L_g, is negative. The minimum requirement for current amplification is therefore

$$\left|2\dot{L}_g\right| > \overline{R_g} + R \tag{7}$$

From Fig. 2 it can be seen that L_g is in the vicinity of 0.2 h/sec (ohms) for the Model 106 generator. Thus the combined network resistance, comprised of the antenna radiation resistance and loss resistance and the generator loss resistance, must be less than 0.4 ohms.

For a dipole to have this low a resistance, it must be operating at frequencies in which the dipole height is much less than a wavelength. Equation (6) shows that the operating frequency (or frequency of the radiated signal) is the frequency at which the generator inductance tunes the antenna. Thus, Eq. (6) states that the antenna reactance must be capacitive at the frequency of operation, which is compatible with a low radiation resistance.

It now becomes clear how this system must operate. The generator drives and tunes the antenna simultaneously. The operating frequency increases monotonically with time because the generator inductance is decreasing monotonically to zero. The antenna radiation resistance also increases monotonically because the antenna is growing in electrical length. When the radiation resistance exceeds 0.4 ohm, the current begins to decay. Therefore, the antenna should be designed such that its radiation resistance reaches 0.4 ohm near the end of the operating period of the generator. The radiated field would then be an oscillating signal, continually growing in amplitude and increasing in frequency until the generator ceases to operate.

The foregoing arguments cannot be supported by use of the RLC equivalent circuit of Fig. 5, which is a poor equivalence at low frequencies. Instead, the equivalent circuit of Fig. 6 was selected, which, as illustrated, is an excellent equivalence to a 4.5-in. dipole over the frequencies of interest. The differential equations for this circuit coupled with the generator circuit were solved numerically, and the results are shown in Figs. 7 and 8. The Model 169 generator has an initial inductance of approximately 18 μh and an operating time of approximately 44 μsec. It can be seen that the Model 169 generator can produce a 4000 V/m electric field at a distance of 1.4 miles.

It is concluded that, by careful design, the directly coupled antenna can radiate field strengths of sufficiently large magnitudes. The

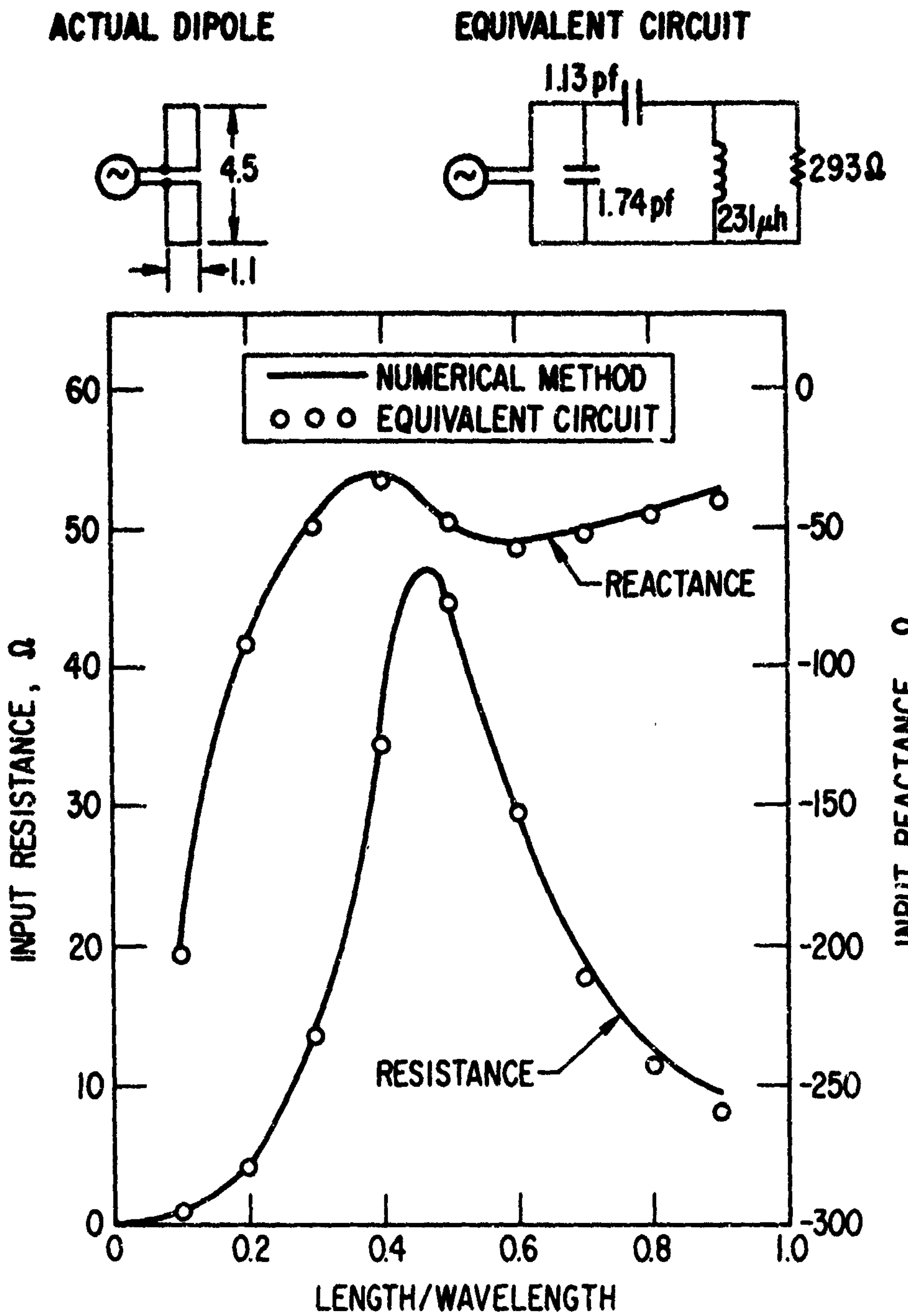


Figure 6. Comparison of calculated antenna input impedance using numerical method and equivalent circuit.

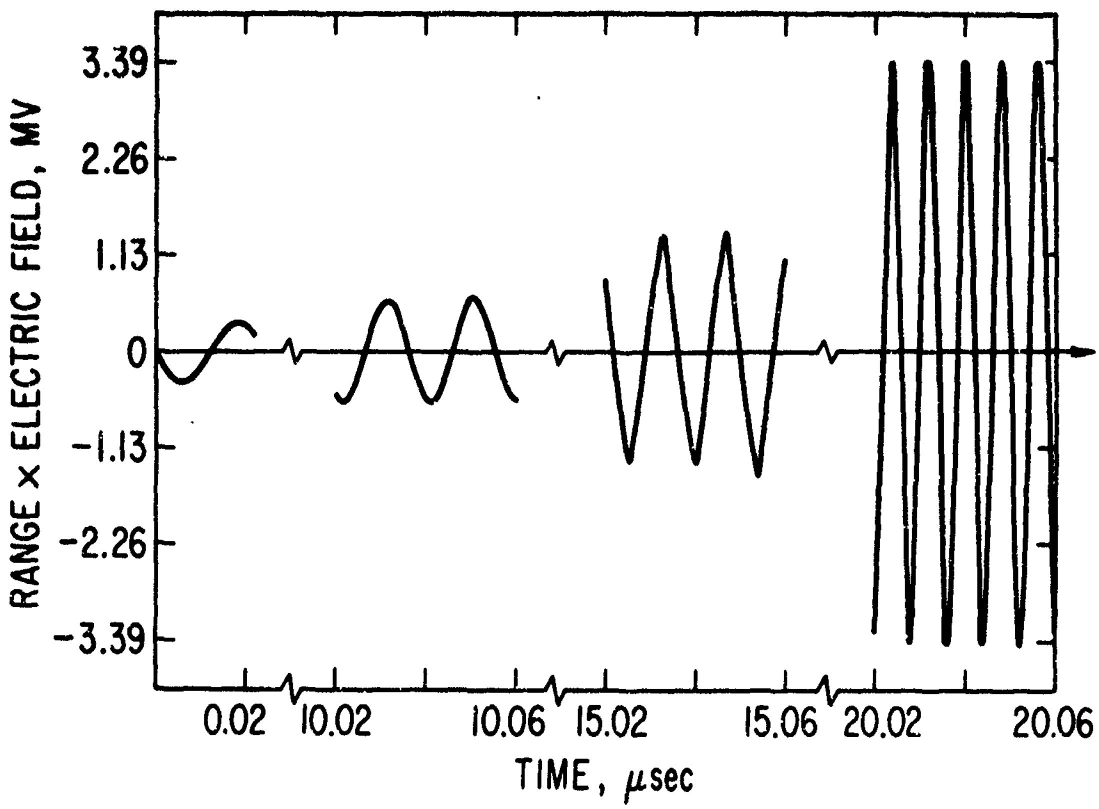


Figure 7. Radiated field for 4.5-in. dipole coupled directly to Sandia Model 106 generator.

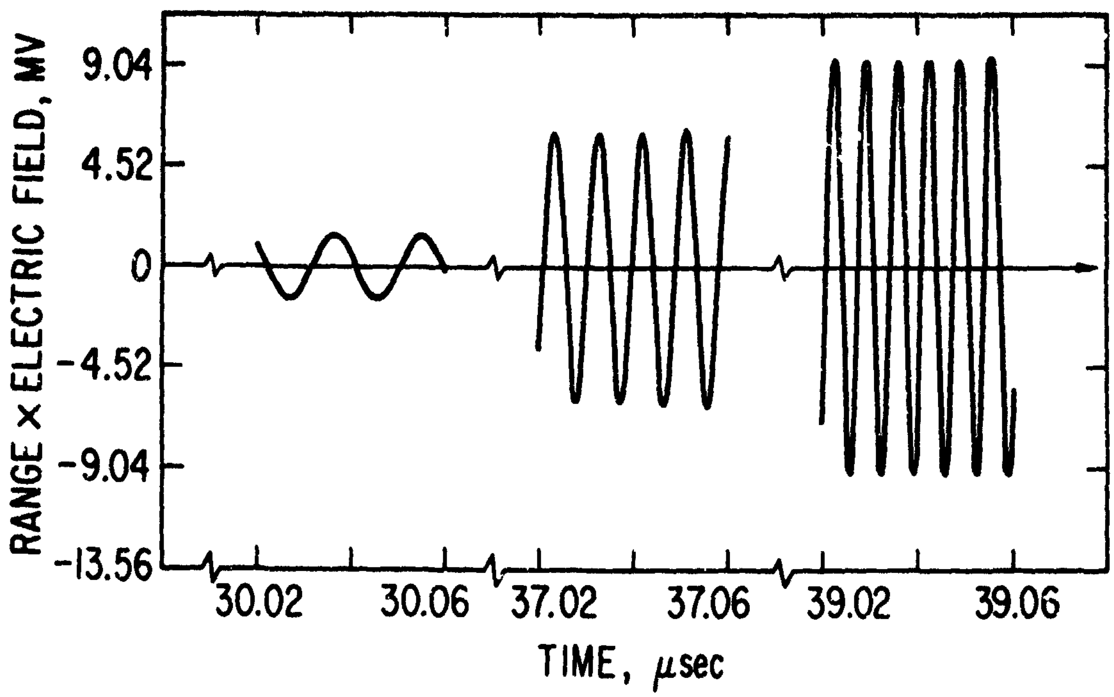


Figure 8. Radiated field for 4.5-in. dipole coupled directly to Sandia Model 169 generator.

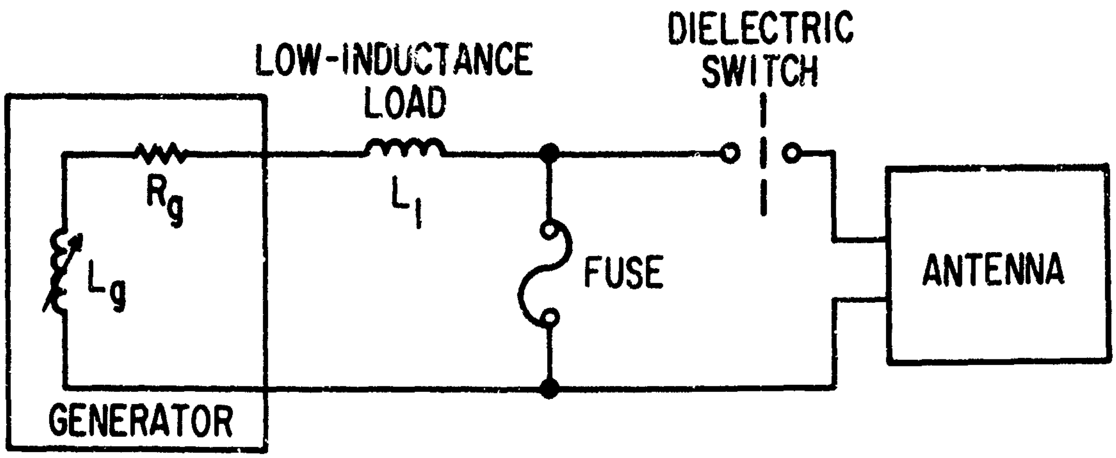
frequency is constantly changing, however, so that the energy in any specified frequency band may be quite small. An even greater concern is the requirement that the dipole be electrically small. Aside from the usual question of efficiency, it is highly conceivable that, at the frequencies of interest, the satellite itself can become a radiator of sufficient strength to cause the total radiation resistance to exceed 0.4 ohm. Therefore, in practice, it may be very difficult to design a directly coupled antenna to have the required low radiation resistance, and an investigation of alternative methods of coupling appears warranted.

D. COUPLING THROUGH SWITCHES

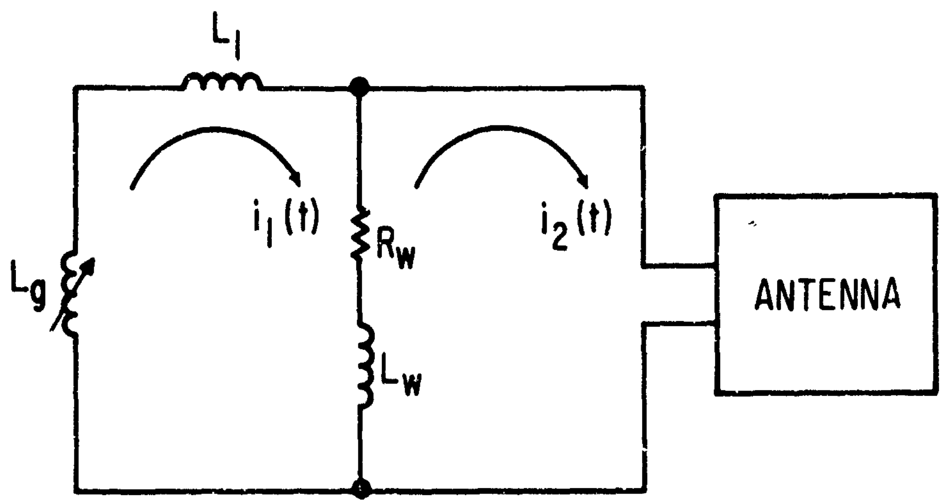
As discussed in Section C, when the explosive generator is coupled to loads with appreciable resistance, attenuation rather than amplification of current is produced. In order to avoid this very stringent condition on the antenna, an alternative is suggested. Consider the circuit of Fig. 9a. The primary circuit consists of the generator and a low inductance load L_1. The dielectric switch remains open as the current in the primary circuit is allowed to reach its peak value (6.6 MA for Model 169). The fuse is a wire so designed that it explodes (bursts) at or near peak current. Just prior to bursting, the resistance of the fuse wire increases drastically (by about a factor of 100) in approximately 1 μsec. The dielectric switch is adjusted so that the voltage spike produced by the exploding wire fuse causes the switch to break down (close).

This concept has been used successfully to reduce the material risetime of explosive generators.[1] For these cases, it was shown that, for a low inductance secondary load, a considerable amount of the primary current flowing at burst time can be transferred into the secondary circuit. The amount of current that can be transferred when the secondary load is an antenna must now be determined.

Equivalent circuits will once again be used to describe the system. A circuit representation is shown in Fig. 9b immediately after the switch has closed. The generator inductance L_g and the fuse wire resistance and inductance



a. Schematic representation.



b. Equivalent circuit.

Figure 9. Schematic representation and equivalent circuit of explosive generator, antenna, and coupling circuit.

R_w and L_w, respectively, will be assumed to be constant over the time scales of interest. The time t is measured after switch closure, and the initial conditions are $i_1(o) = I_{10}$ and $i_2(o) = 0$, where I_{10} is the peak current generated in the primary circuit. As a result of the assumption of constant circuit parameters, the system differential equations become amenable to solution by Laplace transformation. The transformed equations are

$$\left[s(L_g + L_1 + L_w) + R_w\right] I_1(s) - (sL_w + R_w) I_2(s) = (L_g + L_1 + L_w) I_{10} \quad (8)$$

$$-(sL_w) + R_w) I_1(s) + \left[sL_w + R_w + Z(s)\right] I_2(s) = -L_w I_{10} \quad (9)$$

where

$$I_{1,2}(s) = \int_o^\infty i_{1,2}(t)\, e^{-st}\, dt \quad (10)$$

and Z(s) is the equivalent antenna impedance in Laplace transform notation. Because all of the inductances in the primary circuit, including L_g, are now small, it would be expected that the system is resonate at approximately the resonant frequency of the antenna. Therefore, it might be suspected that only a small portion of the primary current can be transferred to the secondary circuit, as the fuse wire resistance will be much smaller than the radiation resistance of the antenna. (The fuse wire resistance must be limited to at most one or two hundredths of an ohm prior to burst time, because high voltages tend to cause internal breakdown in the generator.) Some early calculations showed that this was indeed the case, and it was concluded that, for this system to work, the antenna must be "better matched" to the primary circuit.

This problem is investigated by first casting the equivalent circuit into another form. A circuit driven by two impulse voltage generators is shown in Fig. 10a. This circuit may also represent the system shown in Fig. 9b, as its circuit equations are also Eqs. (8) and (9), provided that the initial conditions are changed to $i_1(o) = i_2(o) = 0$.

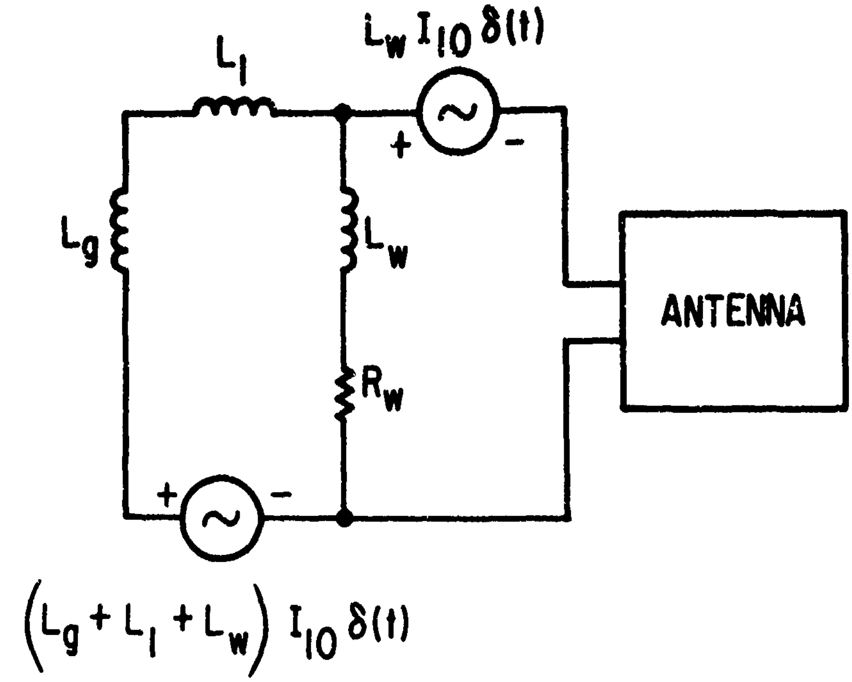
Next, Thévenin's theorem is used to convert this circuit to the form shown in Fig. 10b. It can be seen that the original primary circuit (with an initial current of I_{10}) has been reduced to a single voltage source in series with an impedance (and no initial current). The series impedance can be viewed as a source impedance. The voltage source is now an exponential function, but its time constant is sufficiently large such that appreciable voltage is available at the frequencies of interest.

The problem has been reduced to the standard problem of matching a source impedance to a load (antenna) impedance. A variety of four-terminal networks can be synthesized that will produce perfect matching at a single frequency. An L network comprised of two capacitors has been designed, but this network had not yet been inserted into the equivalent circuit at the time this report was written.

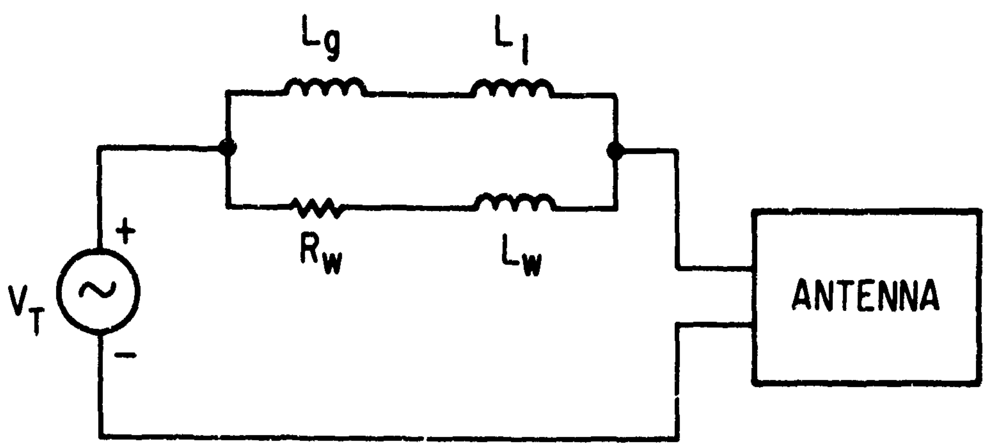
An impedance transformer, such as the one presented in Fig. 11, gives partial matching. It can be shown that, for an ideal transformer of turns ratio 1 : N, maximum current is transferred to the antenna if $N^2 = |Z/Z_s|$, where Z and Z_s are the antenna and source impedances, respectively. Transformer matching was considered first, because the circuit equations can easily be modified to accommodate an ideal transformer.

Some computed results are shown in Fig. 12. The antenna was assumed to be a 200-in. dipole whose arms are bent forward to make an included angle of 40 deg. For this case, the optimum transformer turns ratio was 1 : 8.4. The computed waveform in the absence of a transformer is shown to illustrate the improvement due to matching. Also, it can be seen that the source impedance referred to the secondary now has enough inductance to tune the antenna such that the frequency of oscillation is 23 MHz, or 8 MHz lower than the first resonant frequency of the antenna.

The antenna impedance was approximated by an RLC series circuit that best fits the actual input impedance near 23 MHz. The fuse wire resistance and inductance were assumed to be 2 ohms and 40 nh, respectively. (As stated earlier, R_w may not exceed 0.02 ohm before bursting.) The series combination



a. Two-impulse generator circuit [δ(t) = delta function].



$$V_T = \left(\frac{L_l + L_g}{L_l + L_g + L_w}\right) R_w I_{10} \exp\left(-\frac{R_w t}{L_l + L_g + L_w}\right)$$

b. Two-impulse generator circuit transformed by Thévenin's theorem.

Figure 10. Alternate schematic representation and equivalent circuit of explosive generator, antenna, and coupling circuit.

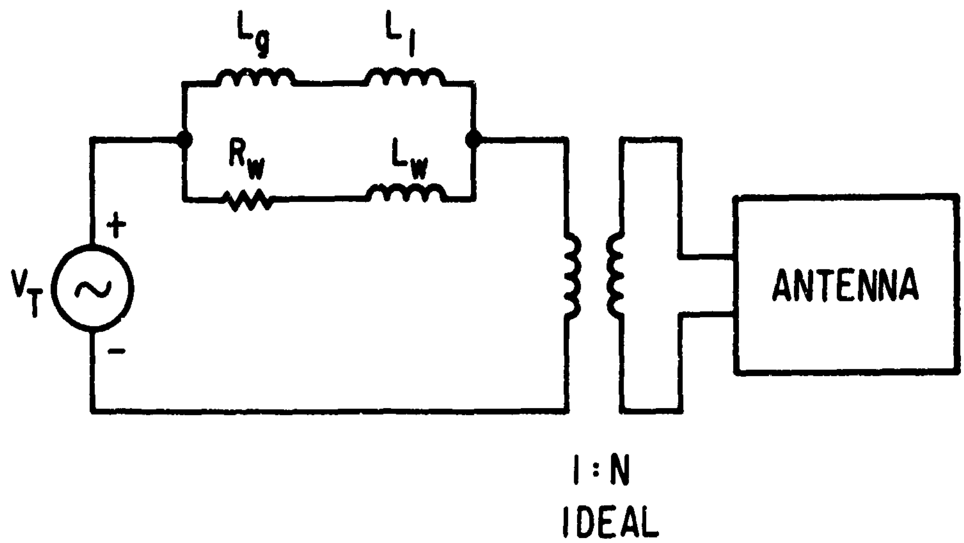


Figure 11. Equivalent circuit of generator, antenna, and switching circuit with impedance transformer coupling.

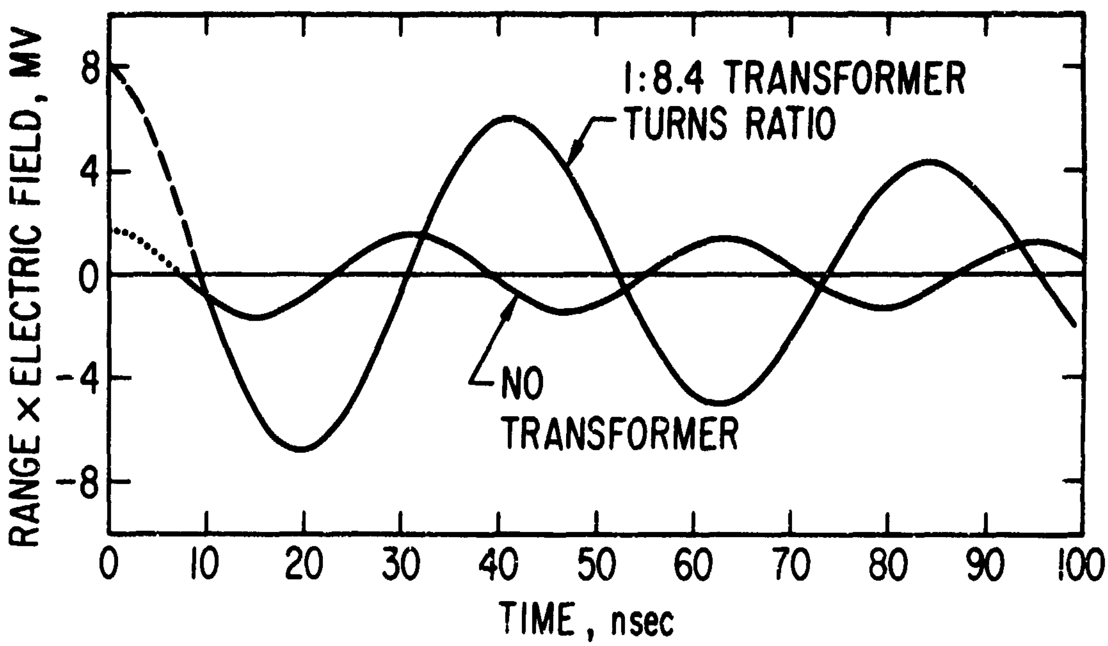


Figure 12. Radiation field waveform for 200-in. bent dipole.

of generator inductance and primary load inductance ($L_g + L_i$) was also assumed to be 40 nh. For expediency, the circuit equations were integrated numerically. The numerical method is capable of accounting for the transient behavior of all of the circuit parameters, including the fuse wire and the switch, but there is insufficient data on these two devices at the present time. Also, as stated earlier, the transient current distribution on the antenna cannot be computed with the present theoretical model. Thus, transient behavior is an unsolved problem, and, for this reason, the first half cycle of both waveforms of Fig. 12 is shown dotted. The second half cycle, however, shows a peak electric field of 4,100 V/m at a distance of one mile.

Computed waveforms for a 100-in. dipole, which is also bent to 40 deg, is shown in Fig. 13. For this case, the optimum transformer turns ratio was 1:6.3. The natural frequency of oscillation is 45 MHz. It can be seen that the electric fields are slightly lower than for the 200-in. dipole, and a peak electric field of 3,100 V/m at a distance of one mile is achieved.

E. DISCUSSION

Calculations have shown that an antenna system weighing less than 500 lb can be designed to produce electric field strengths of several thousand V/m at a distance of one mile. The power supply will be a two-stage explosive generator device similar to the one used on Project Birdseed. Energy will first be delivered to a low inductance load before it switched into an antenna preceded by a matching network.

Throughout the analysis, in addition to carefully defining the assumptions made in the analysis, an attempt was made to point out where data are lacking and where improvements in the theoretical model are needed. Work in these areas is being continued.

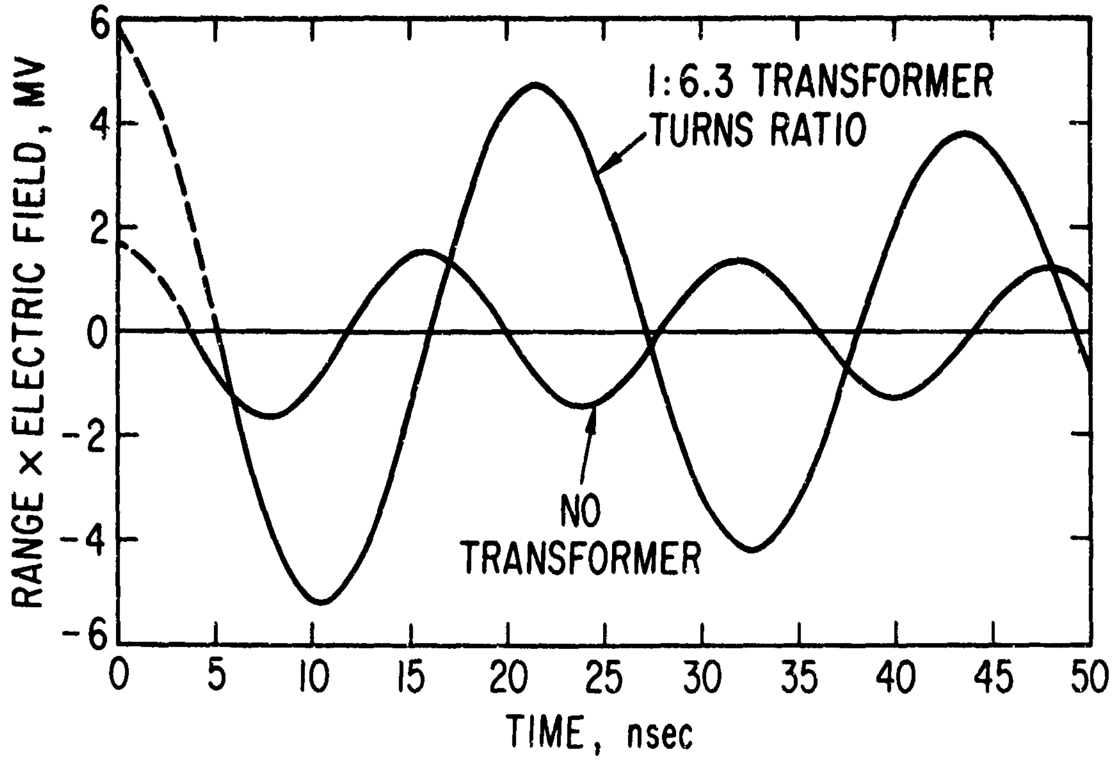


Figure 13. Radiation field waveform for 100-in. bent dipole.

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